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14. ABSTRACT
The project was devoted to advancing understanding of the optical properties of mesoscopic systems of coupled spherical cavities. Using numerical modeling, we studied optical coupling between spherical cavities with detuned whispering gallery mode (WGMs) resonances. The results were found to be in agreement with experiments performed on size-mismatched bispheres with controllable inter-cavity gaps. We observed new type of optical modes, termed “nanojet-induced modes”, in straight chains of microspheres. Due to subwavelength sizes of the periodically focused spots and small propagation losses (<0.1dB/sphere) these modes were shown to be very promising for developing novel devices. The 3D lattices of closely

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Resonant Optical Circuits Based on Coupling Between Whispering Gallery Modes in Dielectric Microresonators

ABSTRACT

The project was devoted to advancing understanding of the optical properties of mesoscopic systems of coupled spherical cavities. Using numerical modeling, we studied optical coupling between spherical cavities with detuned whispering gallery mode (WGMs) resonances. The results were found to be in agreement with experiments performed on size-mismatched bispheres with controllable inter-cavity gaps. We observed new type of optical modes, termed “nanojet-induced modes”, in straight chains of microspheres. Due to subwavelength sizes of the periodically focused spots and small propagation losses (<0.1dB/sphere) these modes were shown to be very promising for developing novel devices. The 3D lattices of closely packed spherical cavities were synthesized by flow-assisted self-assembly with the thickness well controllable up to 100 monolayers. By analogy with the percolation theory we argued that by selecting more uniform spheres it should be possible to achieve an optical percolation threshold for WGM-related transport in such systems. Along with dielectric microspheres we studied GaAs/AlGaAs pillar microcavities where we observed WGMs with Q-factors up to 20000 and small modal volumes. The results of this project are important for developing microprobes for biochemical sensing with subwavelength spatial resolution, reconfigurable filters, sensors and single photon sources.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. A. V. Kanaev, V. N. Astratov, and W. Cai, “Optical coupling at a distance between detuned spherical cavities,” Appl. Phys. Lett. 88, 111111 (2006).
2. S.P. Ashili, V.N. Astratov, and E.C.H. Sykes, “The effects of inter-cavity separation on optical coupling in dielectric bispheres,” Opt. Express 14, 9460-9466 (2006).
3. A.M. Kapitonov and V.N. Astratov, “Observation of nanojet-induced modes with small propagation losses in chains of coupled spherical cavities,” Opt. Lett. 32, 409-411 (2007).
4. V.N. Astratov, and S.P. Ashili, “Percolation of light through whispering gallery modes in 3D lattices of coupled microspheres,” Focus Issue of Optics Express devoted to Physics and Applications of Microresonators 15, 17351-17361 (2007), http://www.opticsexpress.org/abstract.cfm?id=148399
5. V.N. Astratov, S. Yang, S. Lam, B.D. Jones, D. Sanvitto, D.M. Whittaker, A.M. Fox, M.S. Skolnick, A. Tahraoui, P.W. Fry, and M. Hopkinson, “Whispering gallery resonances in semiconductor micropillars,” Appl. Phys. Lett. 91, 071115 (2007).

Number of Papers published in peer-reviewed journals: 5.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. Observation of Whispering Gallery Resonances in Circular and Elliptical Semiconductor Pillar Microcavities (Talk), V.N. Astratov, S. Lam, D. Sanvitto, J.A. Timpson, A. Tahraoui, D.M. Whittaker, and M.S. Skolnick, in Frontiers in Optics, 90th OSA Annual Meeting, Program, p. 168, Rochester, October 8-12, 2006.
2. Observation of Light Propagation via Whispering Gallery Modes in 3-D Networks of Coupled Spherical Cavities (Talk), V.N. Astratov, S.P. Ashili, and A.M. Kapitonov, in Frontiers in Optics, 90th OSA Annual Meeting, Program, p.92, Rochester, October 8-12, 2006
3. Synthesis and Optical Properties of Long Chains of Coupled Spherical Microcavities (Talk), A.M. Kapitonov and V.N. Astratov, in Material Research Society 2007, Technical Program (MRS, 2007), presentation number AA2.7, San-Francisco, April 9-13, 2007.
4. Low Loss WGM Transport in 3D Networks of Coupled Cavities (Talk)
V.N. Astratov, in Photonic West 2007, Technical Program (SPIE, 2007), presentation number 6452-13, San Jose, January 20-26, 2007.
5. Light coupling and Propagation in 3D Lattices of Spherical Cavities (Talk), S.P. Ashili and V.N. Astratov, in Photonic West 2007, Technical Program (SPIE, 2007), presentation number 6452-34, San Jose, January 20-26, 2007.
6. Percolation of Light in 3D Lattices of Coupled Microspheres (Talk), V.N. Astratov and S.P. Ashili, in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO/QELS) and Photonic Applications System Technologies 2007 Technical Digest (Optical Society of America, Washington, DC, 2007), presentation number QTuJ3, Baltimore, May 6-7, 2007.

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. V.N. Astratov, S.P. Ashili, A.M. Kapitonov, and A.V. Kanaev, "Integrated Circuits of Coupled Mircospheres for Optoelectronics Applications," IEEE Proc. of Int. Conf. on Transparent Optical Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Volume 1, pp.77-81, Nottingham, U.K., June 19-23 (2006).
2. A.M. Kapitonov and V.N. Astratov, "Nanojet-Induced Modes in 1D Chains of Microspheres," Proc. of SPIE, Vol. 6452, paper 645205, Photonics West 2007, San Jose, January 20-26, 8pp., 2007.
3. V.N. Astratov, S. Yang, S. Lam, D. Sanvitto, A. Tahraoui, D.M. Whittaker, A.M. Fox, and M.S. Skolnick, "Observation of Whispering Gallery Resonances in Circular and Elliptical Semiconductor Pillar Microcavities," Proc. of Progress in Electromagnetics Research Symposium, Beijing, China, March 26-30, 2007; PIERS Online, Vol. 3, No. 3, 311-314, 2007.
4. V.N. Astratov, S.P. Ashili, and A.M. Kapitonov, "Optical Properties of Mesoscopic Systems of Coupled Microspheres," Proc. of Progress in Electromagnetics Research Symposium, Beijing, China, March 26-30, 2007; PIERS Online, Vol. 3, No. 3, 278-280, 2007.
5. V.N. Astratov, S. Yang, S. Lam, B.D. Jones, D. Sanvitto, D.M. Whittaker, A.M. Fox, and M.S. Skolnick, A. Tahraoui, P.W. Fry, and M. Hopkinson, "High-Quality-Factor WG Modes in Semiconductor Microcavity Pillars with Circular and Elliptical Cross Section," IEEE Proc. of Int. Conf. on Transparent Opt. Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Vol. 4, pp. 170-172, Rome, Italy, July 1-5 (2007).
6. V.N. Astratov, S.P. Ashili, and S. Yang, "Optical Transport Phenomena in Coupled Spherical Cavities," IEEE Proc. of Int. Conf. on Transparent Opt. Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Vol. 3, pp. 65-70, Rome, Italy, July 1-5, (2007).

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(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Shashanka P. Ashili	0.20
Seungmoo Yang	0.50
FTE Equivalent:	**0.70**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Andrey M. Kapitonov	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Vasily N. Astratov	0.15	No
Mohamed A.-Hasan	0.03	No
FTE Equivalent:	**0.18**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Total Number:	

Names of personnel receiving PHDs

NAME	
Shashanka P. Ashili	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Part C
Final Progress Report

I. COVER PAGE

Grant No. W911NF-05-1-0529, Proposal No.: 46699-MS

Resonant Optical Circuits Based on Coupling Between Whispering Gallery Modes in Dielectric Microresonators

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TABLE OF CONTENTS

1. STATEMENT OF THE PROBLEM STUDIED

This project funded by ARO was devoted to the optical properties of coupled spherical cavities. The systems of coupled cavities attracted an increasing interest of photonic community due to novel mechanisms of coupling and propagation of light in such structures. These include configuration interaction and coherent propagation properties, effects of localization of light in disordered lattices of cavities and many other interesting properties. This is a relatively broad area with many materials and structural designs used to create coupled cavities with the most popular designs based on using microrings and disks integrated on the same chip. The examples of such structures include high order filters[1,2], coupled resonator optical waveguides[3-6] (CROW), side-coupled integrated spaced sequences of resonators[7] (SCISSOR) and more sophisticated[8-13] structures. Coupled cavities can also be obtained as periodically arranged defect states[14-16] in photonic crystal platforms or in laterally patterned[17] microcavity structures. Due to controllable dispersion relations for photons these structures can be used for developing chip-scale delay lines, spectral filters and sensor devices.

One of the major requirements to the technology of such systems includes scalability to large number of *uniform* microresonators. The uniformity of cavities is extremely important for achieving efficient *resonant* coupling between the adjacent cavities. This however still remains a major challenge for modern technology[2,6,18]. Indeed, even best established techniques such as semiconductor CMOS-based fabrication[18] provide random variations of the cavity sizes in ~0.1-1% range. This means that the cavities with Q-factors $>10^4$ required for developing most of the applications are randomly detuned leading to large propagation losses in such structures. There are several techniques which can in principle be used for fine tuning of the individual resonances such as free carrier injection in *p*-*i*-*n* junctions in semiconductor structures[19], use of electro-optical[20] or thermo-optical[2,21] effects. However application of these techniques to a large number of resonators integrated on a single chip still remains a challenge.

Another extremely important problem of coupled cavity systems is connected with developing efficient ways of coupling propagating waves from fibers, waveguides or open space to modes localized in individual cavities. This coupling is typically provided in evanescent regime in side-coupled systems such as strip waveguide-to-microring[19,20], tapered fiber-to-microtoroid[21] or fiber-to-microsphere[22] systems. Under critical coupling conditions the efficiency of coupling can be very high (above 90%) however it requires controlling the gap sizes between the fiber/waveguide and the cavity with nanometric accuracy.

The PI of this project [VA] came to this area with a strong background in studies of synthetic opals[23-28] which are 3D lattices of silica nanospheres. In addition the PI [VA] had an extensive experience in studies of photonic crystal waveguides[29-34] and semiconductor microcavities[35-38]. This experience quite naturally led the PI and co-PIs to the idea of using dielectic microspheres with 3-20μm sizes as building blocks of more complicated coupled cavity structures. In these structures the light is confined in individual cavities due to whispering gallery modes (WGMs) with extremely high Q-factors. The optical transport was supposed to be possible due to some sort of evanescent coupling between these high Q cavities. These coupling phenomena have been extremely poorly studied at the time when we initiated this project. Some results have been obtained[39] for coupling between identical spheres which have been selected on the basis of spectroscopic characterization. The regime of critical coupling between an individual sphere and a tapered fiber has been observed[22]. However the coupling mechanisms between size-mismatched spheres have been largely unknown.

The experiments started in the PI's lab in 2003 resulted in observation[40] of the optical transport due to coupling between whispering gallery modes (WGMs) in touching polystyrene spheres. These results were published[40] by the group of PI [VA] in 2004 in Applied Physics Letters. The scattering losses, however, were shown to be rather high (~3dB/sphere) in such circuits. These losses were explained by the role of cavities size disorder (~1%) leading to the random detuning between the cavities WGM eigenstates.

Following this experimental work the PI [VA] in collaboration with the group of co-PI [WC] performed numerical modeling[5] which showed that a highly efficient WGM-related transport with controllable dispersion can be obtained in a chain of microcylinders as a result of controlling the air gaps separating the cavities. In this work, however, as in all previous theoretical studies on this subject the cavities were assumed to be identical.

These preliminary studies showed that the circuits of coupled spherical cavities are highly attractive for developing novel "mesomaterials" with controllable dispersion for photons. Unique property of these circuits highlighted in our proposal submitted to ARO is connected with a principal possibility to micromanipulate with individual cavities. This allows not only building arbitrary coupled cavity structures integrated on the same chip, but also selecting cavities with resonant properties of their WGMs which is a very important property for achieving highly efficient WGM transport. At the same time these studies were at very early stage, and many problems had to be solved in order to develop technology and applications of coupled microspheres. Our project submitted to ARO contained the following major objectives:

- Developing techniques for the fabrication of coupled microspheres circuits to achieve monodispersity of microresonators and the precise control over their arrangement. This also includes developing methods of controlling the intersphere gaps in such structures.

- Developing experimental studies of such circuits aimed at understanding of the mechanisms of optical transport in disordered systems of coupled microresonators.

- Using highly accurate and efficient numerical 3D algorithms for modeling coupling and propagation effects. The focus of these studies was supposed to be on coupling between size-mismatched cavities with detuned eigenstates.

- Developing optoelectronic and sensing applications of such circuits. One of the major objectives was a reduction the scattering losses in such structures.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

2.1. The support of the project and its outcome

The research on coupled microspheres was initiated[5,40] by the PI [VA] and co-PIs [WC and MAH] in 2003. In the group of PI for the first two years this research was developed by a single graduate student supported by the DARPA funding obtained from our Optoelectronics Center. During last two years the group included one postdoc and two graduate students. The primary source of funding for this work was ARO grant W911NF-05-1-0529, Resonant Optical Circuits Based on Coupling Between Whispering Gallery Modes in Dielectric Microspheres, 10/01/05-09/30/07, $150,000 (PI – Dr. V.N. Astratov). In addition, the modeling effort of this work was supported by a NSF grant CCF-0513179 obtained from Division of Computer and Communication Foundations, High Order Numerical Methods for Light Propagation in Micro-Photonics, 07/01/05-06/30/08, $180,000. Jointly these ARO and NSF grants played a key role in obtaining results summarized below.

During two years of ARO funding (10/01/05-09/30/07) the team of PI has published 5 journal articles[41-45] in Applied Physics Letters, Optics Express and Optics Letters along with 6 referred conference proceedings[46-51]. In 2007 the PI organized and edited[52] the Focus Issue of Optics Express devoted to Physics and Applications of Microresonators where one the papers[44] resulted from this project was published. The PI was invited to give 6 invited talks[53-58] at major international and national conferences based on the results of this work. During his sabbatical semester in 2006 he obtained Senior Visiting EPSRC Fellowship in the UK, University of Sheffield, and was invited to give 7 seminars in major European Universities: European Laboratory for Nonlinear Spectroscopy (LENZ) in Florence, Universities of St. Andrews, Southampton, Sheffield, Dortmund, Pavia and CoreCom Company (Milan) affiliated with Pirelli. In addition this work resulted in 6 contributed talks[59-64] at major international and national meetings.

Participation in this project provided the postdoctoral researches and students with many opportunities for further developing their careers both in academia and in DOD organizations. One of the PI's students, Shashanka Ashili, defended Ph.D. thesis[65] on the basis of the results obtained in this work. This student was awarded a postdoctoral Fellowship at the Biodesign and Innovation Program at the University of Missouri-Columbia in 2007. One of the postdoctoral associates, Dr. Andrey Kanaev, who was involved in theoretical modeling in 2005-06 became a contractor at Navy Research Laboratory in 2006. Another postdoctoral associate, Dr. Charles Sykes, involved in fabrication of elastomeric PDMS substrates in 2005 became an assistant professor at Tufts University.

2.2. Research Findings

For each objective we achieved major breakthroughs in this project.

Technology**.** The techniques of self-assembly of microspheres in microflows are developed that allowed obtaining straight chains of more than 100 cavities[43,46,47] in a touching position on the substrate. We developed an original technique[42] of controlling the air gaps between the microspheres with nanometric precision (~20nm) based on using stretchable elastomeric substrates. Using the technique of flow-assisted self-assembly we synthesized 3D lattices of coupled cavities[44,46,49,51] with the thickness controllable from 1 to 100 monolayers. Due to developing techniques of manipulation with microspheres guided by their spectroscopic characterization we achieved supermonodispersive selection of cavities with uniformity ~0.1%.

Experiment and Modeling. We developed many novel experimental techniques[42-45] and numerical modeling techniques[41,45] of studies the optical coupling phenomena in such structures. We significantly advanced the understanding of mechanisms of coupling between size-mismatched cavities with detuned WGMs. The experimental and modeling results obtained in this project constitute its most notable accomplishments, and they are considered in Section 2.3. We achieved five major accomplishments in understanding of properties of such systems:
(i) Modeling of WGM coupling[41] in size-mismatched bispheres,
(ii) Experimental studies of coupling in bispheres[42] with controllable gaps,
(iii) Observation of nanojet-induced modes[43] in chains of coupled cavities,
(iv) Developing concept of percolation of WGMs[44] in 2D & 3D lattices of cavities,
(v) Observation of WGMs[45] in semiconductor micropillars.

Applications. For nanojet-induced modes observed for the first time in this project we reported[43] attenuation ~0.5dB/sphere. It should be noted however that this attenuation is far from limit. In our most recent unpublished work[66] we observed attenuation for these modes ~0.1dB/sphere. This level of attenuation is sufficiently small for developing novel photonic devices based on using nanojet-induced modes. Due to subwavelength sizes of photonic nanojet the chains of spherical cavities can be used as novel microprobes for laser surgery and biochemical sensing. On the other hand developing applications based on using WGMs in filter and sensor structures require selection of supermonodispersive cavities on a larger scale. We showed that the WGM percolation threshold should be achievable[44] in close packed 3D lattices formed by cavities with $Q \sim 10^3$ and with ~1% size dispersion. This allows developing next generation of resonant sensors and arrayed-resonator light emitting devices. The high-Q (20000) WGM resonances with small modal volumes $V \sim 0.3\ \mu m^3$ observed[45] in 4-5 μm Al(Ga)As/GaAs micropillars can be used in cavity quantum electrodynamics experiments with sources of single photons.

2.3. Most Notable Accomplishments

(i) Modeling of WGM coupling in size-mismatched bispheres

Using numerical modeling, we observed[41] new mechanism of optical coupling between spherical dielectric cavities with whispering gallery mode (WGM) resonances. This mechanism can be understood as a Fano resonance between a discrete state (true WGM excited in one of the spheres) and a continuum of “quasi”-WGMs with distorted shape which can be induced in the receiving sphere. It was demonstrated[41] that the strength of coupling depends on energy detuning between WGMs in adjacent cavities.

The central idea of our numerical studies[41] of coupling phenomena is based on using one of the spheres as a source (S) of WGMs and calculating the EM energy deposited in a second receiving (R) sphere. Due to the fact that each resonator produces its own comb of uncoupled WGM

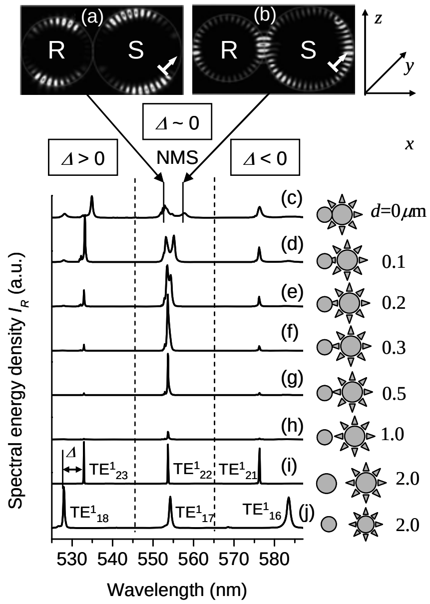

Fig. 1. (a) Antibonding and (b) bonding states. (c-h) Spectral energy density in receiving (R) sphere for different gaps (d). (i,j) spectra of WGM eigentates.

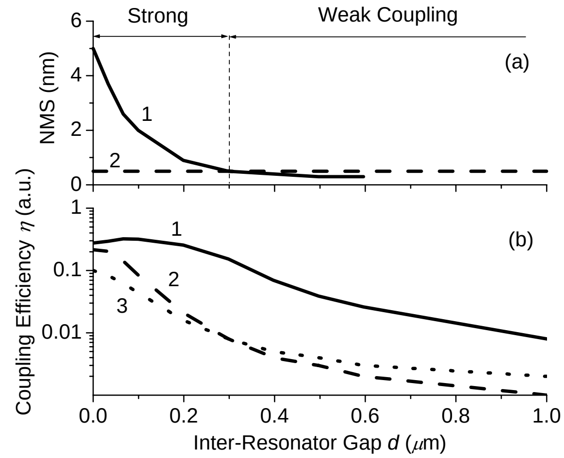

Fig. 2. (a) Normal mode splitting in resonant case as a function of d (line 1). (b) The coupling efficiency (η) as a function of d for different detuning (Δ) between WGMs: 1 - Δ=0.5nm, 2 - Δ=5nm, 3 - Δ=-7.5nm.

frequencies (see Figs. 1 (i) and 1 (j)), we were able to study coupling phenomena for situations with different detuning (Δ) between closest resonances as well as for different separations (d) between the S and R cavities, as illustrated in Figs. 1 (c) -1 (h). In touching case we observed the regime of strong coupling as evident from Figs. 1 (a) and 1 (b) due to the fact that the splitting between coupled components exceed the linewidth of individual resonances. The strongly coupled nature of peaks at 552.9 and 557.9 nm was verified by classical bonding and antibonding molecular states calculated at these wavelengths, as illustrated in Figs. 1 (a) and 1 (b). Increasing the separation between the cavities leads to gradual transition to weak coupling, see Fig. 2 (a). As a measure of the total energy (E_R) deposited in the R cavity we used the area under spectral peaks. A rough estimate of the coupling efficiency (η) was obtained by normalizing E_R by similarly estimated energy (E_S) in the S sphere: $\eta=E_R/E_S$. The results of calculating η for different detuning Δ as a function of d are summarized in Fig. 2 (b). We showed that the coupling between detuned cavities with the efficiency η~0.1-0.2 can be considered as an example of forced oscillations driven by true WGM in S sphere causing the appearance of "quasi"-WGMs with distorted shape in R sphere.

(ii) Experimental studies of coupling in bispheres with controllable gaps

We developed a technique[42] for controlling the separations between the cavities based on placing the spheres at the top of the stretchable substrate, as illustrated in Figs. 3 (a) and 3 (b). By calibrating the tensile strain ($\Delta L/L$) in the substrate one can control the gap sizes between the microspheres with nanometric accuracy (~20nm) according to the formula: $d = (\Delta L/L)(D_S+D_R)/2$, where $D_{S(R)}$ – diameters of two spheres (S and R) under study. The substrates were synthesized using a robust and inert material, namely polydimethylsiloxane (PDMS). To increase its elasticity and the adhesion of the spheres to its surface a smaller than normal

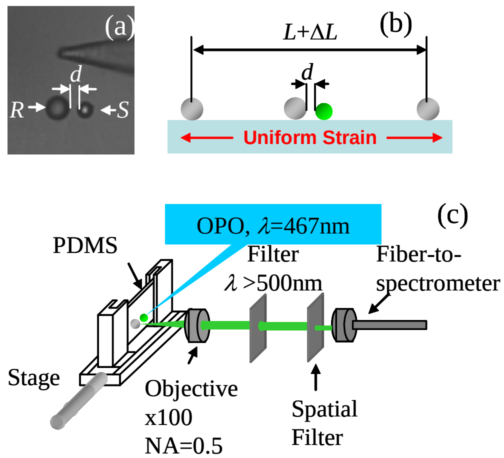

Fig. 3. (a) Image of a bisphere, (b) Stretchable substrate for controlling *d*. (c) Spectroscopic setup.

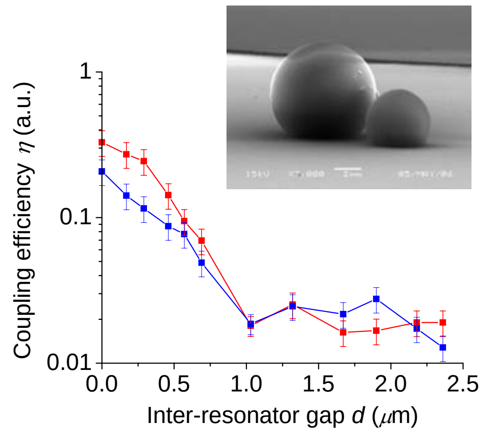

Fig. 4. Efficiency of coupling in bispheres.

concentration (~0.1) of cross-linker was used during the curing step of the manufacture of the PDMS substrate. As illustrated in Fig. 4 the experimental distance dependence of the coupling efficiency[42] can be approximated by exponential law with ~0.3μm attenuation length for d < 1μm. This behavior is in a good qualitative agreement with the results of theoretical modeling[41] performed for smaller (3μm and 2.4μm) spheres. A small level (η~0.02) of scattering detected from R sphere at d>1μm is related to an illumination effect produced by the S sphere.

(iii) Observation of nanojet-induced modes in chains of coupled cavities

Along with studies of WGM-related transport the group of PI observed[43] a completely different nonresonant mechanism of the optical propagation due to periodical focusing effect produced by spheres operating as microlenses. It should be noted that the basic concept of focusing of plane waves by a single microsphere has been revisited[67-69] recently. By using numerical modeling it has been demonstrated that each sphere produces a focused spot termed[67] “nanoscale photonic jet”, with elongated shape and *subwavelength lateral size*.

As illustrated in Figs. 5 (a) and 5 (b) we directly observed[43,46,47,49] such nanojets in long chains of periodically coupled polystyrene microspheres. Such quasi-periodic “nanojet-induced modes” have two interesting properties which are very attractive in terms of developing applications of such systems in microphotonics and sensing. Firstly, the long chains of spheres provide a special type of mode conversion process that lead to formation of nanojets with extremely small lateral sizes. As shown in Fig. 5 (c), away from the source of light (beyond the first decade of spheres) the transverse size of the nanojets appears saturated at the level of ~0.7 μm, which represents the resolution limit of our setup. Secondly, the propagation losses of such nanojet-induced modes are very small away from the sources of light, as illustrated in Fig. 6 (a). It is seen that the attenuation in first few spheres adjacent to the source is several dB/sphere however away from the source the losses are reduced to ~0.5 dB per sphere. In our recent unpublished work we experimentally demonstrated[66] that propagation losses can be smaller than 0.1 dB per sphere. The fundamental limit of losses for these modes is not known at present time. Our preliminary results[66] of 3D FDTD modeling of propagation through the series of microspheres are illustrated

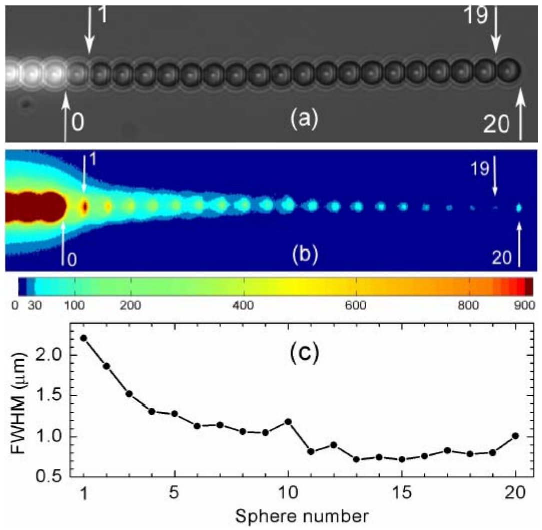

Fig. 5. Visualization of nanojet-induce modes in a locally excited chain of 2.9 μm spheres. (a) Image illustrating that three left spheres are pumped. (b) Scattering image illustrating propagation away from FL source. (c) Cross-sectional width of bright spots illustrating narrowing of nanojets down to diffraction limit.

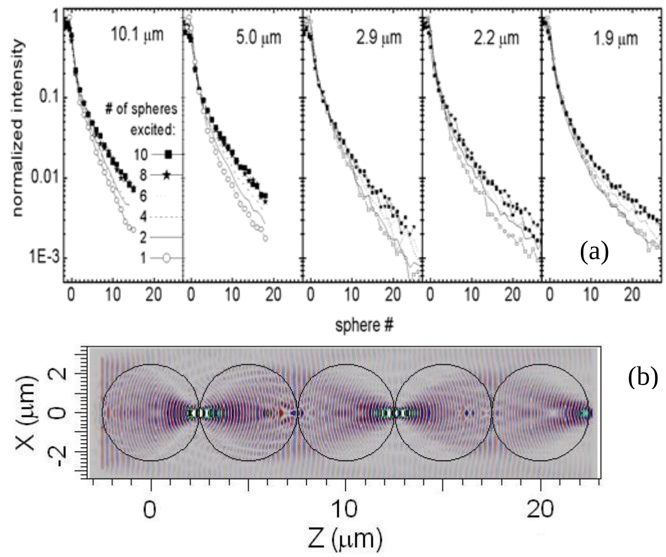

Fig. 6. (a) Intensity of nanojets measured along the chain formed by spheres with different sizes. (b) Pattern of periodical focusing in 5 μm spheres obtained by FDTD numerical modeling.

in Fig. 6 (b). The nanojets are exited by the plane wave illumination at the wavelength which is detuned from the WGM resonances. The field distributions show that the periodicity of nanojets actually corresponds to 2*D*, where *D* is sphere diameter. Thus, in our experiments we simultaneously excited two nanojet-induced modes shifted by *D*. The small size of nanojets in long chains of cavities combined with the low-loss broad band spectral transmission properties of such chains can be used for developing novel micro-probes with subwavelength spatial resolution that will be the subject of our future work.

(iv) Developing concept of percolation of WGMs in 2D & 3D lattices of cavities

A new concept of percolation of light[44] *through WGMs in 2D and 3D lattices of coupled microspheres was recently proposed by the PI and coworker.* The 3D close-packed structures formed by 5 μm dye-doped (Green FL, Duke Scientific Corp.) polystyrene microspheres with ~3% size dispersion were synthesized by the technique[70] of hydrodynamic flow-assisted self-assembly. As shown in Fig. 7 (a) the suspension of spheres was injected into a cell fabricated by sandwiching a mylar film with a rectangular hole between two glass substrates. Submicron scratches fabricated on the surface of the mylar film allowed the liquid to leak out whereas the spheres were trapped inside the cell. The growth of the close-packed structure with ~1 cm^2 area was accelerated under continuous sonication. The thickness (*d*) of the structure was controlled by the mylar films in 5 – 177 μm range. The technique of built-in sources of light employed in this work is schematically illustrated in Fig. 7 (c). The built-in source of WGMs is formed by the focused laser beam with the wavelength tuned to the center of the absorption band of polystyrene microspheres doped with green fluorescent dye. The intensity of the pump laser is almost completely (~90%) absorbed in first three layers of spheres giving rise to dye emission in 500-600 nm range where the spheres are practically transparent.

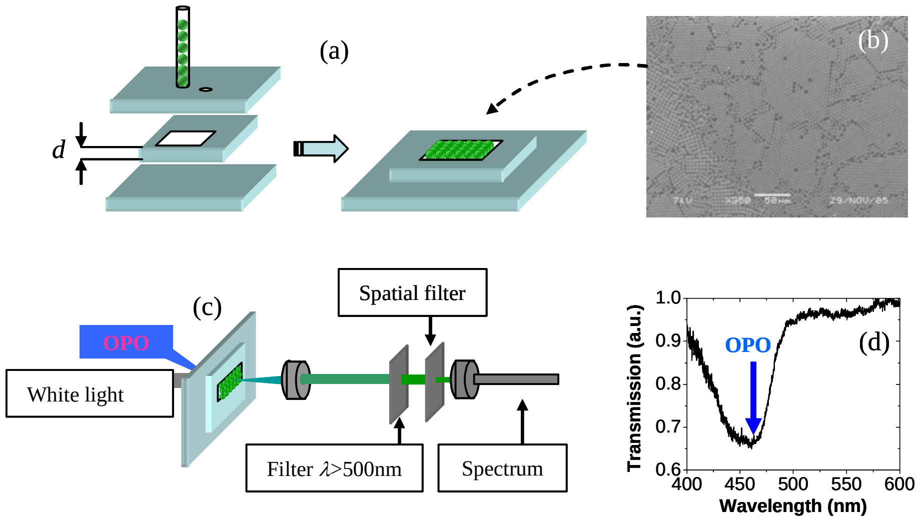

Fig. 7. (a) Sketch of the cell for the hydrodynamic flow-assisted self-assembly of microspheres, (b) SEM image of the top surface of the sample showing its polycrystalline structure, (c) experimental set up, (d) single dye-doped sphere transmission spectrum.

As illustrated in Fig. 8 at small pump intensities we observed[44] maxima in the transmission spectra of such 3D samples determined by the inhomogeneously broadened individual WGM peaks. Most interestingly, with the increasing intensity of the pump each maximum is shown to split into a double-peak structure with the magnitude of splitting (~5nm) that is two times larger than the normal mode splitting which we directly measured from a dielectric bisphere formed by nearly identical 5 μm cavities. We interpret this result as a signature of coupling between multiple cavities with nearly resonant WGMs. The likely explanation of this effect is connected with well-known property of systems of resonant coupled cavities that form two peaks of the normalized group delay[8] at the edges of the CROW transmission band. These peaks provide a distributed feedback for lasing thus explaining why this double peak structure is seen above the lasing threshold. This interpretation is additionally confirmed by the results of measurements of thickness dependence of the FL transmission spectra represented in Fig. 9. It is seen that the intensity of the peaks (in double-peak structures) is *increasing* at high levels of pumping with the increase of the thickness of the sample in the intermediate region from 12 μm to 25 μm whereas the intensity of the FL background is *decreasing* in the same region. Since the FL background propagates diffusively this result indicates that the WGM-related transport is more efficient than classical diffusion of light for such thicknesses.

We developed[44] an approach to understanding the optical transport properties of such systems based on the analogy with the bond percolation problem[71,72] in percolation theory. In this approach, the lattice sites (spheres) are connected with optical “bonds” that are present with probability p depending on the cavities’ size dispersion (assuming $p \approx 1$ in the case of resonance between WGMs). Due to a 3% size disorder, the structures studied in this work are characterized with p~0.01, thus only small clusters of sites connected by bonds can form. However, by selecting more uniform spheres it should be possible to reach a percolation threshold (p_c = 0.1201635 for an fcc lattice[71]) where a giant cluster spans the entire network. This situation means that such lattices should become transparent for the WGM transport irrespective of the

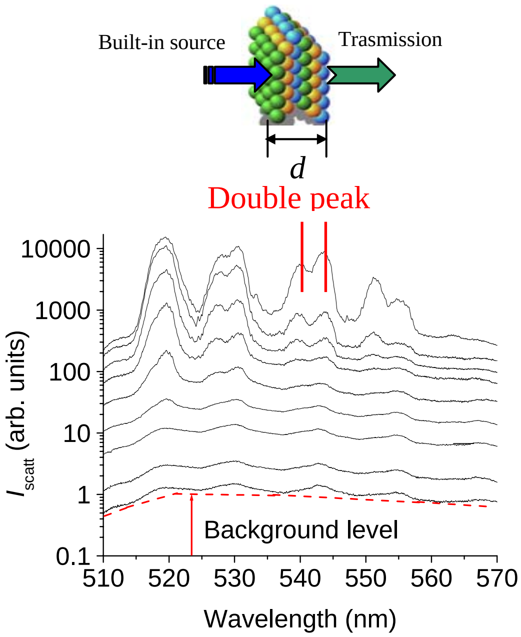

Fig.8. Pump dependence of transmission spectra of 50μm thick lattice formed by 5μm spheres.

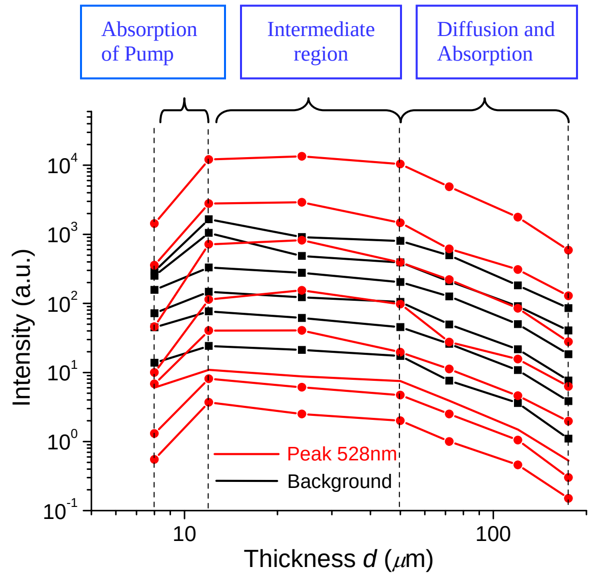

Fig.9. Thickness and pump dependences of transmission intensity of spectral peaks (red) and scattering background (black) in 3D lattices of spheres.

sample thickness. In comparison with single chains of cavities, 3D structures operating above the WGM percolation threshold can tolerate an order of magnitude larger dispersion of spheres sizes. The level of uniformity of spheres required for achieving such WGM percolation threshold depends on their mean size since smaller spheres have smaller Q-factors of their WGM resonances which are easier to overlap. We predict that the WGM percolation threshold should be achievable in close packed 3D lattices formed by cavities with ~10^3 Q-factors of WGMs and with ~1% size dispersion. As an example this situation can be realized using commercially available ~3 μm polystyrene spheres in air or using larger ~10 μm spheres in a liquid environment. Such systems can be used for developing next generation of resonant sensors, microspectrometers, and filters.

(v) Observation of WGMs in semiconductor micropillars

In this Section we present the results[45] obtained during the PI's sabbatical semester in spring 2006 at the University of Sheffield, UK. In this work we observed WGMs in semiconductor micropillars which can be considered as an example of cylindrical cavities with the properties to some extent analogous to microspheres. The subject of these studies was devoted to coupling between emission of a layer of InAs quantum dots (QDs) grown at the center of the cavity and the photonic modes of the cavity. Previously only "photonic dot" states with 3D optical confinement have been observed in such cavities. Whispering gallery modes have been known for microdisks, but they have never been observed in micropillars where the cavity is surrounded with two Bragg mirrors in vertical direction. In our work[45] we observed WGMs in micropillars for the first time and showed some advantages of these modes for developing cavity QED experiments.

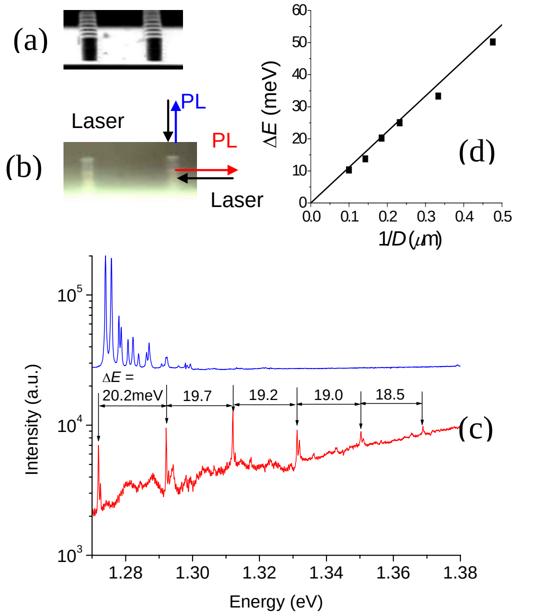

Fig. 10. (a) SEM image of the micropillar array, (b) optical micrograph of pillars, (c) emission spectra of 5.4 μm circular pillars detected from the top (blue) and from the sidewall surface (red) with the WGM mode spacing ΔE indicated, and (d) ΔE vs $1/D$, where D is the pillar diameter.

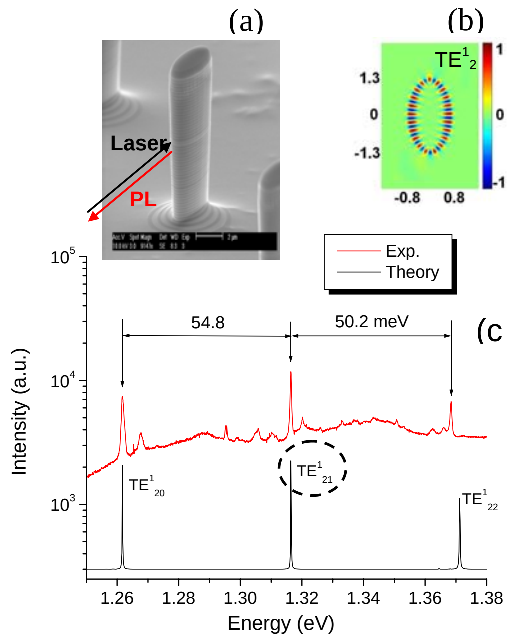

Fig. 11. SEM image of elliptical pillars, (b) em amplitude map for TE_{21}^1 WGM peak, and (c) comparison between the experimental sidewall PL (red) and the spectrum of the WGM peaks (black) calculated for 2.6 × 1.6 μm^2 elliptical pillars.

As illustrated in Fig. 10 we observed high quality (Q up to 20000) WGMs with small modal volumes V~0.3 μm^3 in 4-5 μm Al(Ga)As/GaAs micropillars by employing an experimental geometry in which both excitation and collection of emission is in a direction normal to the sidewalls of the pillars. Similar WGM peaks were detected from the sidewalls of pillars with elliptical cross section, as illustrated in Fig. 11, for 2.6 × 1.6 μm^2 pillars. The Q factors of the WGMs were found to be reduced in such small pillars down to Q~6000 but were still higher than that for photonic dot states (~4000) measured from the top Bragg mirror of the same pillars. As shown in Fig. 11 (c) we also performed a numerical modeling of the WGM spectra in micropillars and obtained an em amplitude maps for WGMs illustrated in Fig. 11 (b). As a result we showed[45,48,50] that WGMs provide at least two times larger values of the figure of merit for strong coupling applications, $Q/\sqrt{V}$, compared to "photonic dot" states in pillars with comparable size. Such micropillars can be used as sources of single photons in cavity quantum electrodynamics experiments with potential applications in quantum information processing.

The work on semiconductor micropillars is closely related to the project on spherical cavities due to the circular symmetry of the resonators leading to similar physical properties of WGMs. In particular it shows a principal possibility to fabricate and study properties of coupled micropillars which can be realized in a different material system at the Optical Center facilities in Charlotte. It was also important in terms of developing WGM modeling techniques in different structures.

2.4. Summary and Outlook

In summary, we developed the technology of circuits of coupled microspheres including capabilities[43,66] of fabrication of straight chains of more than 100 cavities and controlling[42] the air gaps between the spheres with nanometric accuracy. We synthesized 3D lattices of coupled cavities[44,49] with the well controllable thickness from one monolayer up to 100 monolayers of closely packed spherical cavities. Through numerical modeling effort we developed understanding of the mechanisms of optical coupling between cavities with detuned eigenstates[41] and predicted interesting novel properties of such coupling such as quasi-WGMs and Fano-type resonances. We experimentally realized[42] this type of coupling in size-mismatched bispheres. We also studied light-matter coupling in semiconductor pillar systems[45,48,50] where a material oscillator (QD) can interact with different types of photonic modes including "photonic dot" states and WGMs. We observed WGMs in semiconductor micropillars for the first time. We developed techniques of modeling[41,45] of WGM peak positions, *Q*-factors and modal volumes in spherical and pillar cavities. The results of this numerical modeling were found to be in a very good agreement with the experimental data.

Two accomplishments among these results seem to be particularly important for future projects in the context of developing novel photonic devices. One is connected with observation[43] of "nanojet-induced modes" in chains of spherical cavities. These modes are very interesting due to subwavelength sizes of nanojets and small propagation losses. In our most recent unpublished work[66] we observed propagation losses below 0.1dB/sphere. It is also important to note that these modes are much more tolerant to the presence of size disorder of cavities in comparison with WGMs. These small losses clearly open the prospect for device applications of such structures. One of the examples of such structures is connected with assembling microspheres inside a microcapillary tube that would create a mechanically supported system which can be used as a microprobe. Due to mechanical robustness, extremely tight focusing of the beam, high optical throughput and broad spectral transmission properties such microprobes would be useful in a variety of biomedical applications.

Another result with a potential impact on technology of coupled cavity devices is connected with developing concept of percolation of light[44] in disordered lattices of cavities. We predicted that the WGM percolation threshold should be achievable in close packed 3D lattices with $\sim 10^3$ Q-factors of WGMs with ~1% size dispersion. As an example this situation can be realized by using commercially available ~3 μm polystyrene spheres in air or by using enlarged (~10 μm) spheres in a liquid environment. On the basis of our results[44] it seems feasible to achieve criticality of coupling in the latter case. Such structures of critically coupled cavities with percolative WGM transport can be used for multi wavelength detection of biochemical-binding events at the liquid-sphere interface.

A particularly important resource of these studies is connected with developing techniques of sepermonodispersive selection of cavities. In the present project we started developing such techniques and achieved uniformity ~0.1%. These results can be radically improved on the basis of massively parallel manipulation of cavities guided by the spectroscopy. These techniques should result in developing next generation of photonic devices based on supermonodispersive coupled cavities with reduced scattering losses.

BIBLIOGRAPHY

[1] B.E. Little, S.T. Chu, H.A. Haus, J. Foresi, and J.-P. Laine, "Microring resonator channel dropping filters," *J. of Lightwave Technol*. **15**, 998-1005 (1997).
[2] B. E. Little, S. T. Chu, P. P. Absil, J. V. Hryniewicz, F. G. Johnson, F. Seiferth, D. Gill, V. Van, O. King, and M. Trakalo, "Very high-order microring resonator filters for WDM applications," IEEE *Photon. Technol. Lett*. **16**, 2263-2265 (2004).
[3] N. Stefanou and A. Modinos, "Impurity bands in photonic insulators," *Phys. Rev*. B 57, 12127-12133 (1998).
[4] A. Yariv, Y.Xu, R.K. Lee, and A. Scherer, "Coupled-resonator optical waveguide: A proposal and analysis," *Opt. Lett*. **24**, 711-713 (1999).
[5] S. Deng, W. Cai, and V. N. Astratov, "Numerical study of light propagation via whispering gallery modes in microcylinder coupled resonator optical waveguides," *Opt. Express* **12**, 6468-6480 (2004), http://www.opticsexpress.org/abstract.cfm?id=83604
[6] J. K. S. Poon, L. Zhu, G. A. DeRose, and A. Yariv, "Transmission and group delay of microring coupled-resonator optical waveguides," *Opt. Lett*. **31**, 456-458 (2006).
[7] J.E. Heebner, R. W. Boyd, and Q. H. Park, "SCISSOR solitons and other novel propagation effects in microresonator-midified waveguides," *J. Opt. Soc. Am*. B **19**, 722-731 (2002).
[8] M. Sumetsky and B. J. Eggleton, "Modeling and optimization of complex photonic resonant cavity circuits," *Opt. Express* **11**, 381-391 (2003), http://www.opticsexpress.org/abstract.cfm?id=71298
[9] D. D. Smith, H. Chang, and K. A. Fuller, "Whispering-gallery mode splitting in coupled microresonators," *J. Opt. Soc. Am*. B **20**, 1967-1974 (2003).
[10] J. E. Heebner, P. Chak, S. Pereira, J. E. Sipe, and R. W. Boyd, "Distributed and localized feedback in microresonator sequences for linear and nonlinear optics," *J. Opt. Soc. Am*. B **21**, 1818-1832 (2004).
[11] A. B. Matsko, A. A. Savchenkov, D. Strekalov, V. S. Ilchenko, and L. Maleki, "Interference effects in lossy resonator chains," *J. of Modern Opt*. **51**, 2515-2522 (2004).
[12] J. B. Khurgin, "Expanding the bandwidth of slow-light photonic devices based on coupled resonators," *Opt. Lett*. **30**, 513-515 (2005).
[13] S. V. Boriskina, T. M. Benson, P. Sewell, and A. I. Nosich, "Optical modes in 2-D Imperfect Square and Triangular Microcavities," IEEE *J. of Quantum Electron*. **41**, 857-862 (2005).
[14] S. Oliver, C. Smith, M. Rattier, H. Benisty, C. Weisbuch, T.F. Krauss. R. Houdre, and U. Osterle, "Miniband transmission in a photonic crystal coupled-resonator optical waveguide," *Opt. Lett.* **26**, 1019-1021 (2001).
[15] A.D. Bristow, D.M. Whittaker, V.N. Astratov, M.S. Skolnick, A. Tahraoui, T.F. Krauss, M. Hopkinson, M.P. Groucher, and G.A. Gehring, "Defect states and commensurability in dual-period $Al_xGa_{1-x}As$ photonic crystal waveguides," *Phys. Rev.* B **68**, 033303 (2003).
[16] K. Guven and E. Ozbay, "Coupling and phase analysis of cavity structures in two-dimensional photonic crystals," *Phys. Rev*. B **71**, 085108 (2005).
[17] V. Zhuk, D.V. Regelman, D. Gershoni, M. Bayer, J.P. Reithmaier, A. Forchel, P.A. Knipp, and T.L. Reinecke, "Near-field mapping of the electromagnetic field in confined photon geometries," *Phys. Rev*. B **66**, 115302 (2002).
[18] F. Xia, L. Sekaric, and Yu. A. Vlasov, "Ultra-compact optical buffers on a silicon chip," *Nature* Photon. **1**, 65-71 (2007).

[19] S.J. Choi, Z. Peng, Q. Yang, S.J. Choi, and P.D. Dapkus, "Tunable microdisk resonators vertically coupled to bus waveguides using epitaxial regrowth and wafer bonding techniques," *Appl. Phys. Lett.* **84**, 651-653 (2004).
[20] B. Maune, R. Lawson, C. Gunn, A. Scherer, and L. Dalton, "Electrically tunable ring resonators incorporating nematic liquid crystals as cladding layers," *Appl. Phys. Lett.* **83**, 4689-4691 (2003).
[21] D. Armani, B. Min, A. Martin, and K.J. Vahala, "Electrical thermo-optic tuning of ultrahigh-Q microtoroid resonators," *Appl. Phys. Lett.* **85**, 5439-5441 (2004).
[22] M. Cai, O. Painter, and K.J. Vahala, "Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system," *Phys. Rev. Lett*. **85**, 74-77 (2000).
[23] V.N. Astratov, V.N. Bogomolov, A.A. Kaplyanskii, A.V. Prokofiev, L.A. Samoilovich, S.M. Samoilovich, and Y.A. Vlasov, "Optical spectroscopy of opal matrices with CdS embedded in its pores: quantum confinement and photonic band gap effects," *Nuovo Cimento* D **17**, 1349-1354 (1995).
[24] V.N. Astratov, Y.A. Vlasov, O.Z. Karimov, A.A. Kaplyanskii, Y.G. Musikhin, N.A. Bert, V.N. Bogomolov, and A.V. Prokofiev, "Photonic band gaps in 3D ordered FCC silica matrices," *Phys. Lett*. A **222**, 349-353 (1996); "Photonic band structure of 3D ordered silica matrices," *Superlattices & Microstruct*. **22**, 393-397 (1997).
[25] Y.A. Vlasov, V.N. Astratov, O.Z. Karimov, A.A. Kaplyanskii, V.N. Bogomolov, and A.V. Prokofiev, "Existance of a photonic pseudogap for visible light in synthetic opals," *Phys. Rev*. B **55**, R13357-R13360 (1997).
[26] Y.A. Vlasov, V.N. Astratov, A.V. Baryshev, A.A. Kaplyanskii, O.Z. Karimov, and M.F. Limonov, "Manifestation of intrinsic defects in the optical properties of self-organized opal photonic crystals," *Phys. Rev*. E **61**, 5784-5793 (2000).
[27] V.N. Astratov, A.M. Adawi, M.S. Skolnick, V.K. Tikhomirov, V. Lyubin, D.G. Lidzey. M. Ariu, and A.L. Reynolds, "Opal photonic crystals infiltrated with chalcogenide glasses," *Appl. Phys. Lett*. **78**, 4094-4096 (2001).
[28] V.N. Astratov, A.M. Adawi, S. Fricker, M.S. Skolnick, D.M. Whittaker, and P.N. Pusey, "Interplay of order and disorder in the optical properties of opal photonic crystals," *Phys. Rev*. B **66**, 165215 (2002).
[29] V.N. Astratov, R.M. Stevenson, M.S. Skolnick, D.M. Whittaker, S. Brand, I. Culshaw, T.F. Krauss, R.M. De La Rue, and O.Z. Karimov, "Experimental technique to determine the band structure of two-dimensional photonic lattices," *Proc. IEE Optoelectron*., **145**, 398-402 (1998).
[30] V.N. Astratov, I.S. Culshaw, R.M. Stevenson, D.M. Whittaker, M.S. Skolnick, T.F. Krauss, and R.M. De La Rue, "Resonant coupling of near-infrared radiation to photonic band structure waveguides," *J. Lightwave Technol*. **17**, 2050-2057 (1999).
[31] V.N. Astratov, D.M. Whittaker, I.S. Culshaw, R.M. Stevenson, M.S. Skolnick, T.F. Krauss, and R.M. De La Rue, "Photonic band structure effects in the reflectivity of periodically patterned waveguides," *Phys. Rev*. B **60**, R16255-R16258 (1999).
[32] V.N. Astratov, R.M. Stevenson, I.S. Culshaw, D.M. Whittaker, M.S. Skolnick, T.F. Krauss, and R.M. De La Rue, "Heavy photon dispersions in photonic crystal waveguides," *Appl. Phys. Lett*. **77**, 178-180 (2000).
[33] D.M. Whittaker, I.S. Culshaw, V.N. Astratov, and M.S. Skolnick, "Photonic bandstructure of patterned waveguides with dielectric and metallic cladding," *Phys. Rev*. **B**, 073102 (2002).

[34] A.D. Bristow, V.N. Astratov, R. Shimada, I.S. Culshaw, M.S. Skolnick, D.M. Whittaker, A. Tahraoui, and T.F. Krauss, “Polarization conversion in the reflectivity properties of photonic crystal waveguides,” *IEEE J. of Q. El*. **38**, 880-884 (2002).
[35] A. Armitage, M.S. Skolnick, V.N. Astratov, D.M. Whittaker, G. Panzarini, L.C. Andreani, T.F. Fisher, J.S. Roberts, A.V. Kavokin, M.S. Kaliteevski, and M.R. Vladimirova, “Optically induced splitting of bright excitonic states in coupled quantum microcavities,” *Phys. Rev*. B **57**, 14877-14881 (1998).
[36] M. Emam-Esmail, V.N. Astratov, M.S. Skolnick, D.M. Whittaker, and J.S. Roberts, “Asymmetric photoluminescence spectra from excitons in a coupled microcavity,” *Phys. Rev.* B **62**, 1552-1555 (2000).
[37] R.M. Stevenson, V.N. Astratov, M.S. Skolnick, D.M. Whittaker, M. Emam-Ismail, A.I. Tartakovskii, P.G. Savvidis, J.J. Baumberg and J.S. Roberts, “Continuous wave observation of massive polariton redistribution by stimulated scattering in semiconductor microcavities,” *Phys. Rev. Lett.* **85**, 3680-3683 (2000).
[38] R.M. Stevenson, V.N. Astratov, M.S. Skolnick, J.S. Roberts and G. Hill, “Uncoupled excitons in semiconductor microcavities detected in resonant Raman scattering,” *Phys. Rev.* B **67**, 081301(R) (2003).
[39] Mukaiyama, K. Takeda, H. Miyazaki, Y. Jimba, and M. Kuwata-Gonokami, “Tight-binding photonic molecule modes of resonant bispheres,” *Phys. Rev. Lett*. **82**, 4623-4626 (1999).
[40] V.N. Astratov, J.P. Franchak, and S.P. Ashili, “Optical coupling and transport phenomena in chains of spherical dielectric microresonators with size disorder,” *Appl. Phys. Lett.* 85, 5508-5510 (2004).
[41] A. V. Kanaev, V. N. Astratov, and W. Cai, “Optical coupling at a distance between detuned spherical cavities,” *Appl. Phys. Lett*. **88**, 111111 (2006).
[42] S.P. Ashili, V.N. Astratov, and E.C.H. Sykes, “The effects of inter-cavity separation on optical coupling in dielectric bispheres,” *Opt. Express* **14**, 9460-9466 (2006).
[43] A.M. Kapitonov and V.N. Astratov, “Observation of nanojet-inducing modes with small propagation losses in chains of coupled spherical cavities,” *Opt. Lett*. **32**, 409-411 (2007).
[44] V.N. Astratov, and S.P. Ashili, “Percolation of light through whispering gallery modes in 3D lattices of coupled microspheres,” *Focus Issue of Optics Express devoted to Physics and Applications of Microresonators* **15**, 17351-17361 (2007), http://www.opticsexpress.org/abstract.cfm?id=148399
[45] V.N. Astratov, S. Yang, S. Lam, B.D. Jones, D. Sanvitto, D.M. Whittaker, A.M. Fox, M.S. Skolnick, A. Tahraoui, P.W. Fry, and M. Hopkinson, “Whispering gallery resonances in semiconductor micropillars,” *Appl. Phys. Lett.* 91, 071115 (2007).
[46] V.N. Astratov, S.P. Ashili, A.M. Kapitonov, and A.V. Kanaev, “Integrated Circuits of Coupled Mircospheres for Optoelectronics Applications,” IEEE Proc. of Int. Conf. on Transparent Optical Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Volume 1, pp.77-81, Nottingham, U.K., June 19-23 (2006).
[47] A.M. Kapitonov and V.N. Astratov, “Nanojet-Induced Modes in 1D Chains of Microspheres,” Proc. of SPIE, Vol. 6452, paper 645205, Photonics West 2007, San Jose, January 20-26, 8pp., 2007.
[48] V.N. Astratov, S. Yang, S. Lam, D. Sanvitto, A. Tahraoui, D.M. Whittaker, A.M. Fox, and M.S. Skolnick, “Observation of Whispering Gallery Resonances in Circular and Elliptical

Semiconductor Pillar Microcavities," Proc. of Progress in Electromagnetics Research Symposium, Beijing, China, March 26-30, 2007; PIERS Online, Vol. 3, No. 3, 311-314, 2007.

[49] V.N. Astratov, S.P. Ashili, and A.M. Kapitonov, "Optical Properties of Mesoscopic Systems of Coupled Microspheres," Proc. of Progress in Electromagnetics Research Symposium, Beijing, China, March 26-30, 2007; PIERS Online, Vol. 3, No. 3, 278-280, 2007.

[50] V.N. Astratov, S. Yang, S. Lam, B.D. Jones, D. Sanvitto, D.M. Whittaker, A.M. Fox, and M.S. Skolnick, A. Tahraoui, P.W. Fry, and M. Hopkinson, "High-Quality-Factor WG Modes in Semiconductor Microcavity Pillars with Circular and Elliptical Cross Section," IEEE Proc. of Int. Conf. on Transparent Opt. Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Vol. 4, pp. 170-172, Rome, Italy, July 1-5 (2007).

[51] V.N. Astratov, S.P. Ashili, and S. Yang, "Optical Transport Phenomena in Coupled Spherical Cavities," IEEE Proc. of Int. Conf. on Transparent Opt. Networks – ICTON06, Special Section on Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light, Vol. 3, pp. 65-70, Rome, Italy, July 1-5, (2007).

[52] V.N. Astratov, "Introduction: Physics and Applications of Microresonators," *Opt. Express* **15**, 17171 (2007).

[53] V.N. Astratov (Invited talk), Frontiers in Optics, 89th OSA Annual Meeting, Tucson, Arizona, October 16-20, 2005. Title: "Circuits of Microspheres for Applications in Integrated Optoelectronics and Controllable Delay Lines".

[54] V.N. Astratov (Invited talk), Int. Conf. on Transparent Opt. Networks – ICTON'06, Special Section on *Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light*, Nottingham, UK, June 19-20, 2006. Title: "Integrated Complex Networks of Coupled Microspheres for Optoelectronics Applications".

[55] V.N. Astratov (Invited talk), Int. Progress in Electromagnetic Research Symposium, PIERS-2007, Beijing, China, March 26-30, 2007. Title: "Observation of Whispering Gallery Resonances in Circular and Elliptical Semiconductor Pillar Microcavities".

[56] V.N. Astratov (Invited talk), Int. Progress in Electromagnetic Research Symposium, PIERS-2007**,** Beijing, China, March 26-30, 2007. Title: "Optical Properties of Mesoscopic Systems of Coupled Microspheres".

[57] V.N. Astratov (Invited talk), Int. Conf. on Transparent Opt. Networks – ICTON'07, Special Section on *Microresonators and Photonic Molecules: Trapping, Harnessing and Releasing Light*, Rome, Italy, July 1-5, 2007. Title: "Optical Transport Phenomena in Coupled Spherical Cavities".

[58] V.N. Astratov (Invited talk), Photonics West 2008, San Jose, January 2008. Title: "Optical Transport in Coupled Spherical Cavities with Tunable Whispering Gallery Modes."

[59] Observation of Whispering Gallery Resonances in Circular and Elliptical Semiconductor Pillar Microcavities (Talk), V.N. Astratov, S. Lam, D. Sanvitto, J.A. Timpson, A. Tahraoui, D.M. Whittaker, and M.S. Skolnick, in Frontiers in Optics, 90th OSA Annual Meeting, Program, p. 168, Rochester, October 8-12, 2006.

[60] Observation of Light Propagation via Whispering Gallery Modes in 3-D Networks of Coupled Spherical Cavities (Talk), V.N. Astratov, S.P. Ashili, and A.M. Kapitonov, in Frontiers in Optics, 90th OSA Annual Meeting, Program, p.92, Rochester, October 8-12, 2006

[61] Synthesis and Optical Properties of Long Chains of Coupled Spherical Microcavities (Talk)

A.M. Kapitonov and V.N. Astratov, in Material Research Society 2007, Technical Program (MRS, 2007), presentation number AA2.7, San-Francisco, April 9-13, 2007.

[62] Low Loss WGM Transport in 3D Networks of Coupled Cavities (Talk)
V.N. Astratov, in Photonic West 2007, Technical Program (SPIE, 2007), presentation number 6452-13, San Jose, January 20-26, 2007.

[63] Light coupling and Propagation in 3D Lattices of Spherical Cavities (Talk)
S.P. Ashili and V.N. Astratov, in Photonic West 2007, Technical Program (SPIE, 2007), presentation number 6452-34, San Jose, January 20-26, 2007.

[64] Percolation of Light in 3D Lattices of Coupled Microspheres (Talk)
V.N. Astratov and S.P. Ashili, in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO/QELS) and Photonic Applications System Technologies 2007 Technical Digest (Optical Society of America, Washington, DC, 2007), presentation number QTuJ3, Baltimore, May 6-7, 2007.

[65] S.P. Ashili, "Optical Properties of Polycrystalline Opals and Mesoscopic Systems of Coupled Spherical Cavities," Ph.D. thesis, defended on November 7th, 2007.

[66] S. Yang and V.N. Astratov, "Nanojet-Induced Modes in Coupled Spherical Cavities with Losses Smaller than 0.1dB/Sphere," to be submitted to *Appl. Phys. Lett*. in January 2008.

[67] Z. Chen, A. Taflove, and V. Backman, "Photonic nanojet enhancement of backscattering of light by nanoparticles: a potential novel visible-light ultramicroscopy technique," *Opt. Express* **12**,1214-1220 (2004), http://www.opticsexpress.org/abstract.cfm?id=79442

[68] S. Lecler, Y. Takahura, and P. Meyrueis, "Properties of a three-dimensional photonic jet," *Opt. Lett*. **30**, 2641-2643 (2005).

[69] Z. Chen, A. Taflove, and V. Backman, "Highly efficient optical coupling and transport phenomena in chains of dielectric microspheres," *Opt. Lett*. **31**, 389-391 (2006).

[70] B. Gates, D. Qin, and Y. Xia, "Assembly of nanoparticles into opaline structures over large areas," *Adv. Mater*. **11**, 466-469 (1999).

[71] C.D. Lorenz and R.M. Ziff, "Precise determination of the bond percolation thresholds in finite-size scaling corrections for the sc, fcc, and bcc lattices," *Phys. Rev*. E **57**, 230-236 (1998).

[72] For a recent review on compex networks see: R. Albert and A.-L. Barabasi, "Statistical mechanics of complex networks," *Review of Modern Physics* **74**, 47-97 (2002).